

# The $\phi \rightarrow \eta\pi^0\gamma$ decay

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## Abstract

Rare radiative decay  $\phi \rightarrow \eta\pi^0\gamma$  was studied with SND detector at VEPP-2M electron-positron collider and its branching ratio was measured:  $B(\phi \rightarrow \eta\pi^0\gamma) = (0.88 \pm 0.14 \pm 0.09) \cdot 10^{-4}$ . Significant contribution of the  $a_0(980)\gamma$  intermediate state was observed in the decay. The result is based on total integrated luminosity corresponding to  $2 \cdot 10^7$  produced  $\phi$  mesons.

*PACS:* 13.25.-k; 13.65.+i; 14.40.-n

*Keywords:*  $e^+e^-$  collisions; Vector meson; Detector

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**Introduction.** The first observation of the rare radiative decay

$$\phi \rightarrow \eta\pi^0\gamma, \quad (1)$$

and measurement of its branching ratio were performed in Novosibirsk by SND detector at VEPP-2M  $e^+e^-$  collider [1, 2]. The analysis was based on data collected by SND in 1996 [3]. Later the results were confirmed by CMD-2 group in their recent publication [4]. Results of the present work are based on analysis of all SND data collected in the vicinity of  $\phi$  meson in 1996–1998 [5].

Reaction (1) is especially interesting in connection with the scalar  $a_0(980)$  meson problem, which is being actively discussed in the literature. At present there is no generally accepted viewpoint on the nature of  $a_0$ , its quark structure is still not well established, and several models exist including modification of  $q\bar{q}$  scheme [6],  $K\bar{K}$  molecular model [7], and 4-quark model [8]. It was suggested in [9] that the decay  $\phi \rightarrow a_0(980)\gamma \rightarrow \eta\pi^0\gamma$  may serve as a probe of the  $a_0$ -meson quark structure. Theoretical predictions for the decay branching ratio vary from  $10^{-5}$  for

the simple two-quark and  $K\bar{K}$  molecular models up to  $10^{-4}$  in the 4-quark model [9, 10]. There also exist some models in which high rate of the decay (1) can be achieved without assumption of 4-quark structure of the  $a_0$  meson [11]. Another possible mechanism of the  $\phi \rightarrow \eta\pi^0\gamma$  decay is  $\phi \rightarrow \rho^0\pi^0, \rho \rightarrow \eta\gamma$ . The vector meson dominance model prediction for this branching ratio is  $5 \cdot 10^{-6}$  [9, 10]. Detailed study of the  $\phi \rightarrow \eta\pi^0\gamma$  decay may provide decisive information on  $a_0(980)$  meson problem.

**Experiment.** The SND [12] is a universal nonmagnetic detector. Its main part is a 3-layer electromagnetic calorimeter consisted of 1630 NaI(Tl) crystals. The energy resolution of the calorimeter for photons can be described as  $\sigma_E/E = 4.2\%/\sqrt[4]{E(GeV)}$  [13], the angular resolution is close to  $1.5^\circ$ . The solid angle coverage is 90% of  $4\pi$  steradian.

The data used for the study of  $\phi \rightarrow \eta\pi^0\gamma$  decay were collected in 1996–1998 [5]. Nine successive scans of the energy range 980–1040 MeV were performed. The data were collected at 16 beam energy points. The total integrated luminosity in the experiment is  $12 \text{ pb}^{-1}$  and

total number of produced  $\phi$  mesons —  $2 \cdot 10^7$ .

**Event Selection.** Main sources of background for the process under study

$$e^+e^- \rightarrow \phi \rightarrow \eta\pi^0\gamma \rightarrow 5\gamma \quad (2)$$

are the following  $\phi$ -meson decays:

$$e^+e^- \rightarrow \phi \rightarrow \pi^0\pi^0\gamma \rightarrow 5\gamma \quad (3)$$

$$e^+e^- \rightarrow \phi \rightarrow \eta\gamma \rightarrow 3\pi^0\gamma \rightarrow 7\gamma, \quad (4)$$

$$e^+e^- \rightarrow \phi \rightarrow K_S K_L \rightarrow \text{neutrals} \quad (5)$$

and a nonresonant process

$$e^+e^- \rightarrow \omega\pi^0 \rightarrow \pi^0\pi^0\gamma \rightarrow 5\gamma. \quad (6)$$

The process (4) does not produce 5 $\gamma$  events directly but can mimic the process (2) due to either merging of close photons or loss of soft photons through openings in the calorimeter. The process (5) contributes due to  $K_S \rightarrow \pi^0\pi^0$  decay accompanied by either nuclear interaction of the  $K_L$  meson or its decay in flight.

Primary event selection was based on simple criteria: the number of reconstructed photons is equal to five, there are no tracks in the drift chamber, the

total energy deposition  $E_{tot}$  ranges from 0.8 up to 1.1 of the center of mass energy  $2E_0$ , the total transverse momentum of photons is less than  $0.15E_{tot}/c$ . In order to suppress background from the processes (4) and (5) a special “photon quality” parameter  $\zeta$  [14] was used. For  $i$ -th reconstructed photon the  $\zeta_i$  is a minus logarithm of likelihood for the corresponding transverse energy deposition profile observed in the calorimeter to be produced by a single photon. For multiphoton events  $\zeta$  is defined as a maximum  $\zeta_i$ . The cut  $\zeta < 0$  suppresses the background from the process (4) by a factor of two, reducing the detection efficiency for actual 5- $\gamma$  events by only 8%. To suppress beam background photons which appear mostly in the calorimeter areas closest to the beam and are relatively soft, additional cut was imposed on polar angles of the two softest photons in an event:  $32^\circ < \theta_4, \theta_5 < 148^\circ$ .

For events which passed the cuts described above kinematic fitting under two alternative hypotheses was performed and corresponding values of  $\chi^2$  calculated:

- an event is one of the process  $e^+e^- \rightarrow$

$5\gamma$ ; the  $\chi^2$  value is denoted as  $\chi_{5\gamma}^2$ ;

- an event is one of the process  $e^+e^- \rightarrow 3\gamma$  with two additional stray photons; the  $\chi^2$  value is denoted as  $\chi_{3\gamma}^2$ .

The following restrictions on the  $\chi_{5\gamma}^2$  and  $\chi_{3\gamma}^2$  parameters were imposed:  $\chi_{5\gamma}^2 < 25$ ,  $\chi_{3\gamma}^2 > 20$ . The first restriction causing only 5% loss of actual  $\phi \rightarrow \eta\pi^0\gamma$  events reduces background from the process (4) by approximately 30% and almost completely removes background from the process (5). The second cut suppresses background from the processes  $\phi \rightarrow \eta\gamma \rightarrow 3\gamma$ ,  $\phi \rightarrow \pi^0\gamma \rightarrow 3\gamma$ ,  $e^+e^- \rightarrow 2\gamma, 3\gamma$  (QED).

For further background suppression, an event configuration (the photon energies and angles after 5- $\gamma$  kinematic fitting) was compared using modification of kinematic fitting technique developed in the work [15] with ones expected for the process (2) and background processes (3), (6). Corresponding measure of discrepancy  $P$  is an increase of  $\chi^2$  for a 5- $\gamma$  event after application of additional requirements on intermediate states for each tested hypothesis. The following hypotheses were considered:

- an event is a cascade reaction  $e^+e^- \rightarrow X\gamma$ ,  $X \rightarrow \eta\pi^0$  where  $X$  is some intermediate particle; the  $P_{\eta\pi\gamma}$  parameter and invariant masses of photon pairs, presumably produced in the decays of  $\pi^0$  and  $\eta$  mesons ( $M_\pi$  and  $M_\eta$ ) were calculated;
- an event is a cascade reaction  $e^+e^- \rightarrow X\gamma$ ,  $X \rightarrow \pi^0\pi^0$ ; the  $P_{\pi\pi\gamma}$  parameter was calculated;
- an event is of the process  $e^+e^- \rightarrow \omega\pi^0, \omega \rightarrow \pi^0\gamma$ ; parameter  $M_\omega$  — an invariant mass of  $\pi^0\gamma$  pair from the  $\omega \rightarrow \pi^0\gamma$  decay, was calculated;

Relative contributions from the background processes (3) and (6) vary with  $m_{\eta\pi}$  — invariant mass of  $\eta\pi^0$  pair. At  $m_{\eta\pi} < 975$  MeV the background from the process (3) becomes significant. Additional cut  $P_{\pi\pi\gamma} > 2$  suppresses it by a factor of three reducing detection efficiency for the process (2) by only 12%. At  $m_{\eta\pi} \leq 900$  MeV the dominant background comes from the process (6). In this region restriction  $M_\omega < 725$  MeV removes background almost completely.

The scatter plot for  $M_\eta$  invariant mass versus  $E_{\gamma max}/E_{beam}$  — normalized en-

ergy of the most energetic photon in the selected events is shown in fig.1, where two regions are distinguishable:

$E_{\gamma max}/E_{beam} > 0.68$  dominated by background from the reaction (4) with a nearly uniform  $M_{\eta}$  distribution and

$E_{\gamma max}/E_{beam} < 0.68$  where the background is small and the points are grouped close to  $\eta$ -meson mass. The  $M_{\eta}$  vs.  $M_{\pi^0}$  distribution in events with  $E_{\gamma max}/E_{beam} < 0.68$  is shown in fig.2. It is clearly peaked at  $\pi^0$  and  $\eta$ -meson masses.

For final selection of  $\phi \rightarrow \eta\pi\gamma$  events, in addition to the cuts described above the restriction  $E_{\gamma max}/E_{beam} < 0.68$  practically completely removing background from the process (4) and  $P_{\eta\pi\gamma} < 7$  were applied. The  $P_{\eta\pi\gamma}$  distribution for the selected events is shown in fig.3. The cut  $P_{\eta\pi\gamma} < 7$  roughly corresponds to the restrictions  $|M_{\pi^0} - m_{\pi^0}| < 30$  MeV and  $|M_{\eta} - m_{\eta}| < 30$  MeV, where  $m_{\pi^0}$  and  $m_{\eta}$  are the  $\pi^0$  and  $\eta$  masses. Total of 39 events were found with expected background of  $3.2 \pm 0.7$  events. In the region  $7 < P_{\eta\pi\gamma} < 15$  ten events were found in agreement with estimated  $8.9 \pm 0.4$   $\eta\pi^0\gamma$  events plus  $6 \pm 1$  background events. Thus, after cuts described above the event sample still contains background

of about 10%. After background subtraction  $35.8 \pm 6.3$  events of the process  $e^+e^- \rightarrow \eta\pi^0\gamma$  are left.

**Data analysis.** Fig.4 shows  $\cos \alpha$  distribution for the selected events, where  $\alpha$  is an angle between the recoil photon in the reaction (2) and  $\eta$ -meson momentum in the  $\eta\pi^0$  rest frame. Estimated background of 3.2 events is subtracted. Experimental distribution is in a good agreement with the simulated one, which was initially isotropic as expected for a scalar intermediate state. Its visible slope is a consequence of the  $E_{\gamma max} < 0.68$  cut. Such an agreement may be considered as an evidence that  $\eta\pi^0$ -system is produced in a scalar state ( $P(\chi^2) = 61\%$ ). In fig.5 the  $\cos \theta_{\gamma}$  distribution is shown. The  $\theta_{\gamma}$  is a polar angle of the recoil photon in the reaction (2). It also agrees ( $P(\chi^2) = 22\%$ ) with the simulated distribution  $(1 + \cos^2 \theta_{\gamma})$  expected for production of a scalar particle and photon.

Detection efficiency obtained by simulation must be corrected for event loss due to additional spurious photons and for imprecise simulation of parameters used in the event selection cuts. Corresponding correction factor was obtained

from experimental data. To this end cross section of the process (6) was measured using the selection criteria similar to those described above for the process (2). The result was compared with our earlier measurement [16]. It was found that simulation overestimates detection efficiency for the process (2) by 5%.

In the Table 1 the numbers of selected events, detection efficiencies, and measured differential branching ratios  $dB/dm$  as a function of  $m_{\eta\pi}$  invariant mass are listed. The detection efficiencies and  $dB/dm$  values are given at middle points of the corresponding invariant mass bins. Uniformly distributed background of 3 events was subtracted. The detection efficiency averaged over the experimental invariant mass spectrum is equal to 2.1%.

Fitting of energy dependence of the experimental cross section by the sum of the resonant cross section of the process (2) and energy-independent background results in

$$B(\phi \rightarrow \eta\pi^0\gamma) = (0.88 \pm 0.14 \pm 0.09) \cdot 10^{-4}, \quad (7)$$

The main sources of systematic error here are uncertainties in the measured

cross section of the process (6) and in average detection efficiency due to large statistical error of the observed  $\eta\pi^0$  invariant mass spectrum.

In fig.6 the dependence of the measured  $\phi \rightarrow \eta\pi^0\gamma$  decay branching ratio on the invariant mass of the  $\eta\pi^0$  pair is shown. In spite of smaller recoil photon phase space at high  $\eta\pi^0$  invariant masses the observed mass spectrum shows enhancement in this region. This means that  $\eta\pi^0$  system is produced in some resonant state. The only known resonance which have relevant mass and quantum numbers is  $a_0(980)$  and the observed enhancement at large  $\eta\pi^0$  invariant masses can be described as manifestation of  $\phi \rightarrow a_0\gamma$  decay. Known  $\phi \rightarrow \rho^0\pi^0, \rho \rightarrow \eta\gamma$  decay mechanism must produce  $\eta\pi^0$  pairs with smaller invariant masses and as was already mentioned its branching ratio is much smaller than observed one, although its amplitude should be taken into account in the approximation of the whole mass spectrum in future high statistics experiments. For  $M_{\eta\pi} > 900$  MeV we have:

$$B(\phi \rightarrow \eta\pi^0\gamma) = (0.46 \pm 0.13) \cdot 10^{-4}. \quad (8)$$

**Discussion.** Since the experimental data show large contribution from the  $\phi \rightarrow a_0\gamma$  decay an attempt was made to approximate observed invariant mass spectrum in assumption of pure  $\phi \rightarrow a_0\gamma$  and assuming decay dynamics as described in the work [9]. This hypothesis gives rather good approximation of the experimental data. The fitting curve is shown in fig.6 ( $P(\chi^2) = 61\%$ ). The following optimal values of the  $a_0$ -meson parameters were obtained:

$$\begin{aligned} M_{a_0} &= 995^{+52}_{-10} \text{ MeV} \\ g_{a_0 K^+ K^-}^2 / 4\pi &= (1.4^{+9.4}_{-0.9}) \text{ GeV}^2 \\ g_{a_0 \eta \pi}^2 / 4\pi &= (0.77^{+1.29}_{-0.20}) \text{ GeV}^2 \end{aligned} \quad (9)$$

The corresponding fitting curve is shown in fig.6. The optimum value of the ratio  $g_{a_0 \eta \pi} / g_{a_0 K^+ K^-} = 0.75^{+0.52}_{-0.32}$  within experimental errors satisfies the relation between coupling constants  $g_{a_0 \eta \pi} = \sqrt{2/3} \cdot g_{a_0 K^+ K^-}$  obtained in [8] in the assumption of 4-quark structure of  $a_0$  meson. If we fix this ratio at its 4-quark model prediction, the optimal values of other fit parameters become:

$$\begin{aligned} M_{a_0} &= 994^{+33}_{-8} \text{ MeV} \\ g_{a_0 K^+ K^-}^2 / 4\pi &= (1.05^{+0.36}_{-0.25}) \text{ GeV}^2 \end{aligned} \quad (10)$$

The mass  $M_{a_0}$  is in agreement with the PDG value 983.4 MeV [17].

Comparison with (8) shows that about 50% of the observed branching ratio (7) corresponds to  $M_{\eta\pi} > 900$  MeV and the observed invariant mass spectrum is consistent with the model [9]. Thus it can be assumed, that the  $a_0\gamma$  intermediate state dominates in this decay. Other decay mechanisms may contribute, for example  $\phi \rightarrow \rho^0 \pi^0, \rho \rightarrow \eta\gamma$ , although rough estimation shows, that its contribution can be neglected at present level of experimental errors (7). Assuming pure  $\phi \rightarrow a_0\gamma$  decay, we get

$$B(\phi \rightarrow a_0\gamma) = (0.88 \pm 0.17) \cdot 10^{-4}. \quad (11)$$

**Conclusions.** In this work, using experimental data corresponding to about  $2 \cdot 10^7$  produced  $\phi$  mesons, 36 events of the  $\phi \rightarrow \eta\pi^0\gamma$  decay were found. The measured branching ratio of this decay  $B(\phi \rightarrow \eta\pi^0\gamma) = (0.88 \pm 0.14 \pm 0.09) \cdot 10^{-4}$  is in agreement with our previous result  $B(\phi \rightarrow \eta\pi^0\gamma) = (0.83 \pm 0.23) \cdot 10^{-4}$  [2], based on analysis of a part of the experimental statistics, as well as with the CMD-2 measurement:  $B(\phi \rightarrow \eta\pi^0\gamma) = (0.90 \pm 0.24 \pm 0.10) \cdot 10^{-4}$

[4]. Observed enhancement in the  $\eta\pi^0$ -pair invariant mass spectrum at large masses shows large contribution of  $a_0\gamma$  intermediate state. Assuming dominance of this mechanism we obtain  $B(\phi \rightarrow a_0\gamma) = (0.88 \pm 0.17) \cdot 10^{-4}$ .

**Acknowledgement.** The authors express their gratitude to N.N.Achasov for fruitful discussions.

This work is supported in part by “Russian Fund for Basic Researches” (Grant No. 99-02-16813), “Russia Universities” Fund (Grant No. 3H-339-00) and STP “Integration” Fund (Grant No 274).

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### Figure captions

- *Figure 1:* Distribution of  $M_\eta$  — reconstructed mass of  $\eta$  meson versus the energy of the most energetic photon in the event  $E_{\gamma max}/E_{beam}$ .
- *Figure 2:* Distribution of  $M_\eta$  — reconstructed mass of  $\eta$  meson versus  $M_\pi$  — reconstructed mass of  $\pi^0$  for events with  $E_{\gamma max}/E_{beam} < 0.68$ .
- *Figure 3* The  $P_{\eta\pi\gamma}$  distribution. Points with error bars - experimental data. Histogram — simulated signal from  $\phi \rightarrow \eta\pi^0\gamma$  decay corresponding to branching ratio of  $0.9 \cdot 10^{-4}$ , shaded histogram — estimated background from the  $e^+e^- \rightarrow \omega\pi^0$  and  $\phi \rightarrow \eta\gamma, f_0(980)\gamma$  processes.
- *Figure 4* The  $\cos \alpha$  distribution.  $\alpha$  is an angle between recoil photon and  $\eta$  meson in the  $\eta\pi^0$  rest frame for selected  $\eta\pi^0\gamma$  events. Points with error bars - experimental data, histogram - simulation of the process (1) with  $BR = 0.9 \cdot 10^{-4}$ .
- *Figure 5* Recoil photon polar angle distribution for selected  $\eta\pi^0\gamma$  events. Points with error bars -

experimental data, histogram - simulation of the process (1) with  $BR = 0.9 \cdot 10^{-4}$ .

- *Figure 6*  $M_{\eta\pi}$  invariant mass spectrum. The fitted curve corresponds to  $M_{a_0} = 995^{+52}_{-10} \text{ MeV}$   $g_{a_0 K^+ K^-}^2 / 4\pi = (1.4^{+9.4}_{-0.9}) \text{ GeV}^2$   $g_{a_0 \eta \pi}^2 / 4\pi = (0.77^{+1.29}_{-0.20}) \text{ GeV}^2$

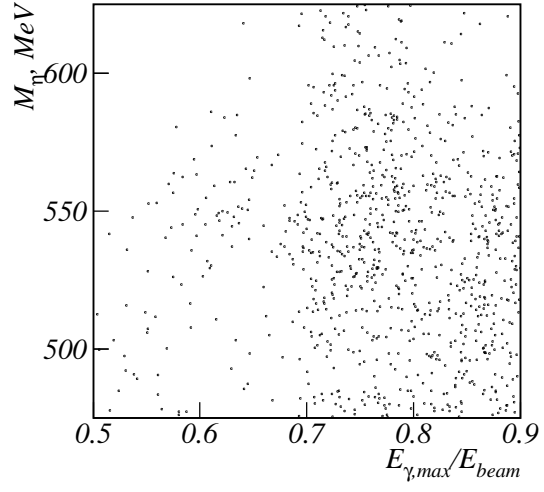


Figure 1: Distribution of  $M_\eta$  — reconstructed mass of  $\eta$  meson versus the energy of the most energetic photon in the event  $E_{\gamma \max} / E_{\text{beam}}$ .

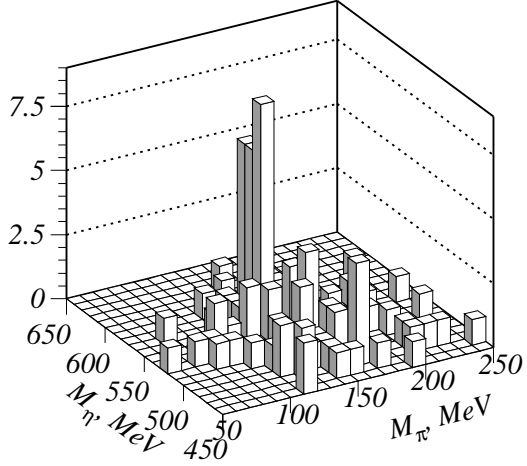


Figure 2: Distribution of  $M_\eta$  — reconstructed mass of  $\eta$  meson versus  $M_{\pi^0}$  — reconstructed mass of  $\pi^0$  for events with  $E_{\gamma \max} / E_{\text{beam}} < 0.68$ .

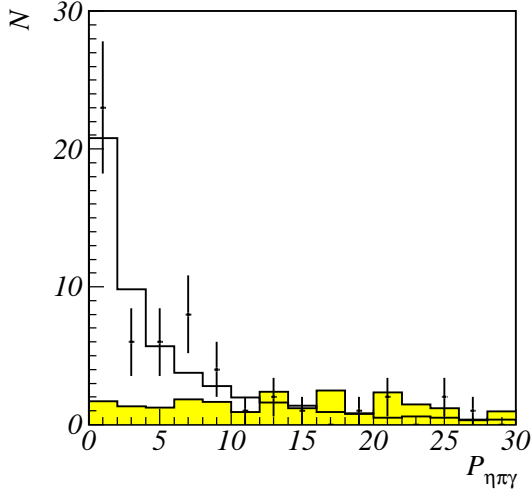


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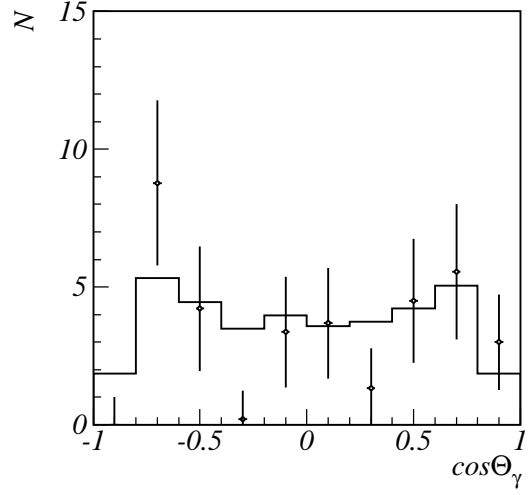


Figure 5: Recoil photon polar angle distribution for selected  $\eta\pi^0\gamma$  events. Points with error bars - experimental data, histogram - simulation of the process (1) with  $BR = 0.9 \cdot 10^{-4}$ .

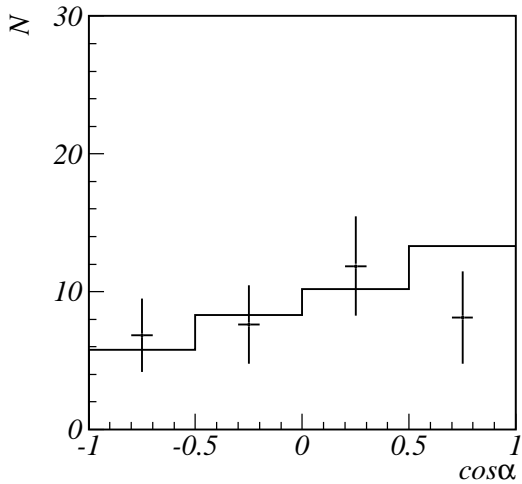


Figure 4: The  $\cos\alpha$  distribution.  $\alpha$  is an angle between recoil photon and  $\eta$  meson in the  $\eta\pi^0$  rest frame for selected  $\eta\pi^0\gamma$  events. Points with error bars - experimental data, histogram - simulation of the process (1) with  $BR = 0.9 \cdot 10^{-4}$ .

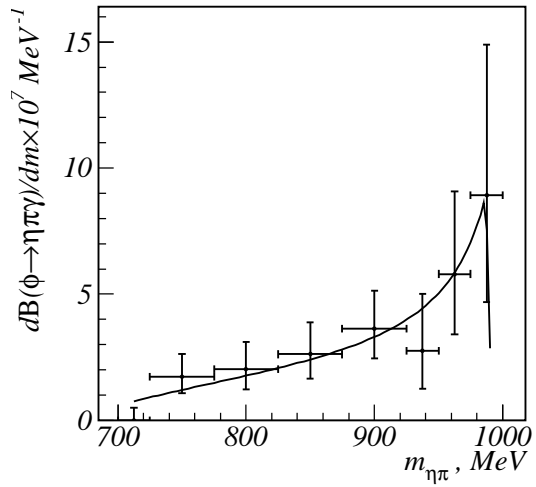


Figure 6:  $M_{\eta\pi}$  invariant mass spectrum. The fitted curve corresponds to  $M_{a_0} = 995^{+52}_{-10}$  MeV  $g_{a_0 K^+ K^-}^2/4\pi = (1.4^{+9.4}_{-0.9})\text{GeV}^2$   $g_{a_0 \eta\pi}^2/4\pi = (0.77^{+1.29}_{-0.20})\text{GeV}^2$

Table 1: The number  $N$  of found  $\phi \rightarrow \eta\pi^0\gamma$  decay events, detection efficiency  $\epsilon$ , and measured  $dB/dm$  as a function of  $m_{\eta\pi}$  — the  $\eta\pi^0$  invariant mass.

$m_{\eta\pi}, MeV$	$N$	$\epsilon$	$dB/dm \cdot 10^7$ ( $MeV^{-1}$ )
700-725	0	0.039	$0 + 0.5$
725-775	5	0.029	$1.7^{+0.9}_{-0.7}$
775-825	6	0.026	$2.0^{+1.1}_{-0.8}$
825-875	7	0.024	$2.6^{+1.3}_{-1.0}$
875-925	9	0.023	$3.6^{+1.5}_{-1.2}$
925-950	3	0.018	$2.8^{+2.3}_{-1.5}$
950-975	5	0.016	$5.8^{+3.3}_{-2.4}$
975-1000	4	0.011	$8.9^{+6.0}_{-4.2}$